Powering Solutions and Technology Options

(for the Muon Acceleration stage)

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F. Batsch (CERN)
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Layout of the presentation

- Power and Energy for the Muon Accelerator
- The power converter panorama for RCS and fast pulses
- The two harmonics generic circuit
- Energy storage capacitors technology

Values from excel sheet
F. Batsch, H. Daimerau.

Power and Energy: a general frame

	RCS2
Total Accelerator length [km]	6
Injection Energy [GeV]	330
Extraction Energy [GeV]	750
Ramping field in NC magnets [T]	-1.8 ÷ 1.8
Ramp time Tramp [ms]	1.12
Repetition time Trep [ms]	100
dB/dt [T/s]	3200
NC magnet length [m]	2438
SC magnets length [m]	1416
NC dipole gap (hxw) [mmxmm]	30x90

$$E_{gap\ B_{max}} = \frac{B_{max}^2}{2\ \mu_0}\ .L_{NCmags}.h_{gap}.w_{gap} = 8.5\ \text{MJ}$$

...but: the total NRG of the dipole magnets is higher. Depending upon the layout of the magnet and the requested field quality, there could be a factor of two or even higher

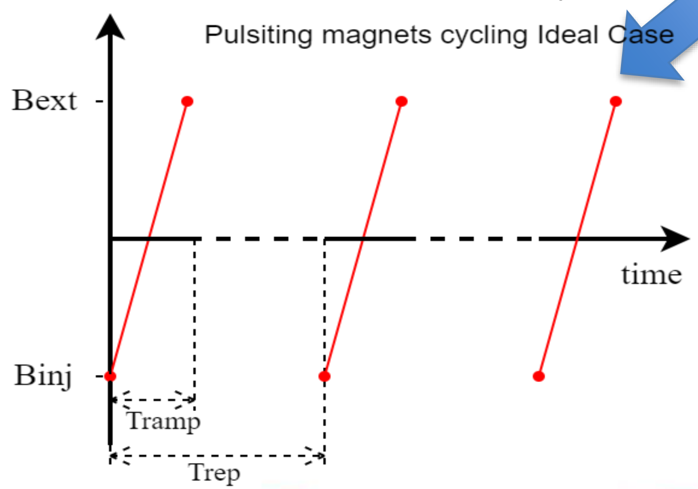
$$E_{mag} \approx 2 \cdot E_{gap\ B_{max}} = 16.9\ \text{MJ}$$

Not so big in value but must be delivered very quickly
To be minimized in magnet design.

$$P(t) = \frac{2 \cdot E_{mag}}{T_{ramp}/2} = 52GW$$

The 52GW must always be considered together with the 10Hz repetition frequency

For the linear ramp case

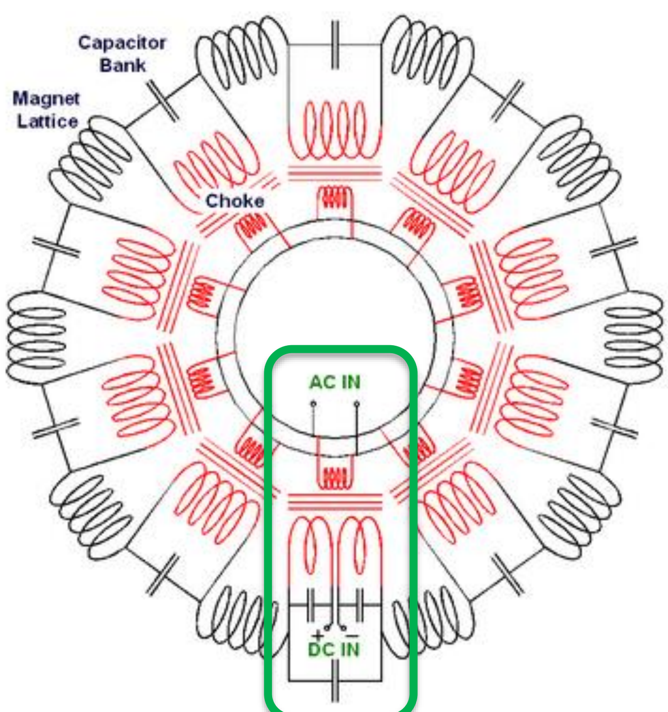


- High repetition frequency (10 Hz)
- Very high number of total pulses (continuous operation)
- Average Energy Content (17MJ)
- Very high peak power (50GW)
- Accuracy and reproducibility control requirements (tbd)

What powering systems are on use today in similar applications?

Rapid Cycling Synchrotron from power system perspective

RCS widely used circuit is known as White circuit



High repetition frequency 10÷50 Hz. LC resonance with magnets, minimizes power taken from AC network. With or without DC contribution.

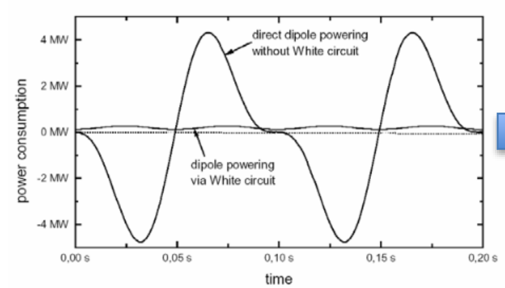


Fig. 2: BESSY II power consumption with/without a White circuit

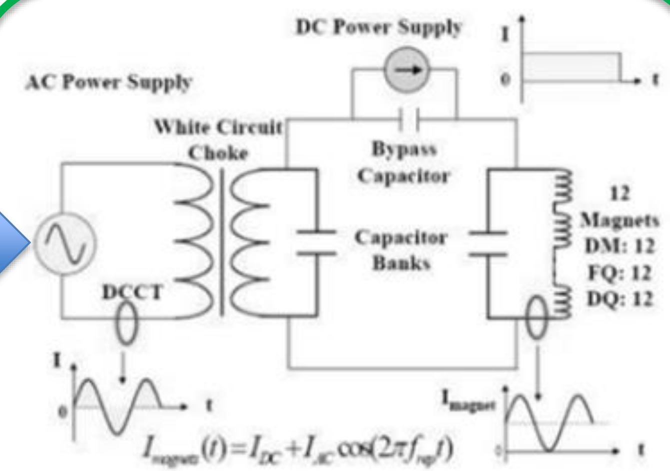


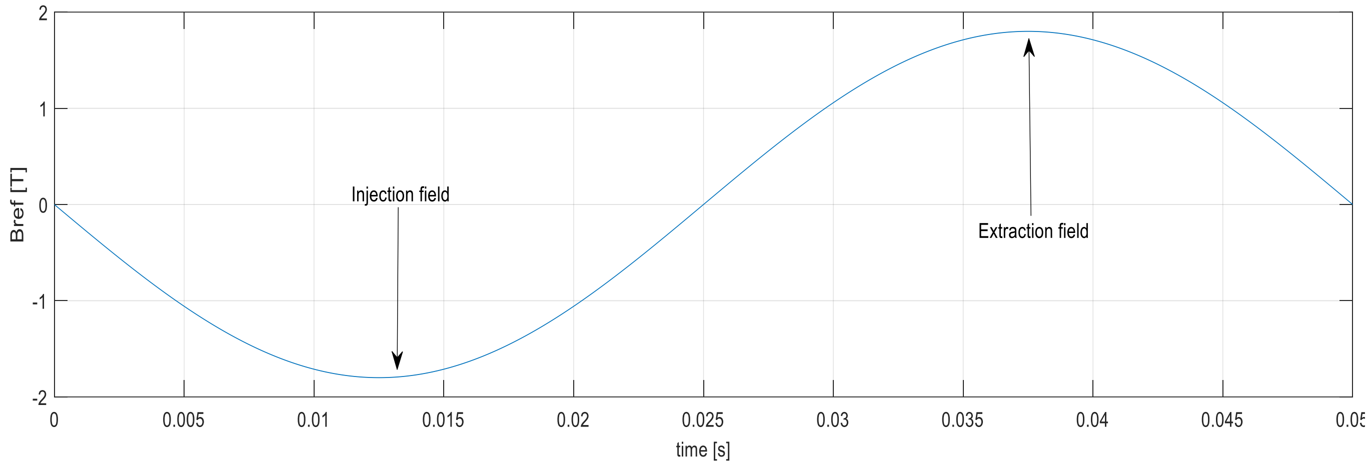
Fig. 28: White circuit schematics

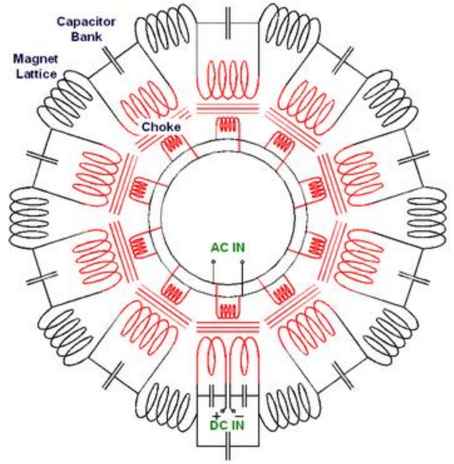
Very much used in "booster synchrotron" in light sources up the years 2000.
Application examples include:

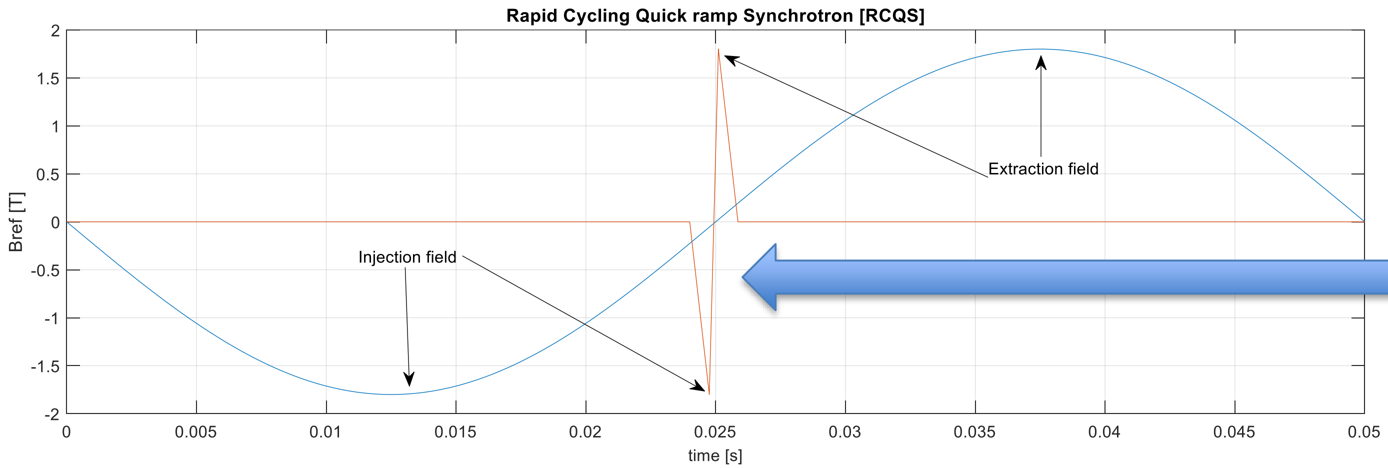
- BESSY II (Helmholtz Zentrum Berlin. Light source) booster synchrotron. 10Hz repetition frequency
- ISIS (Rutherford Appletoin Laboratory Uk. Neutron source) proton booster. 50Hz repetition frequency
- DESY II (Hamburg. Light source) booster. 12.5Hz repetition frequency
- ESRF (Grenoble. Light source). 10Hz repetition frequency
- …

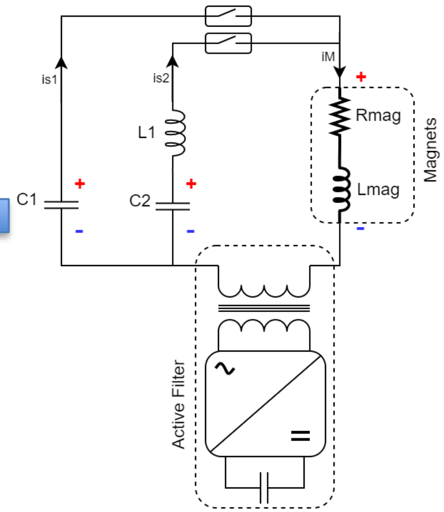
Rapid Cycling Synchrotron from power system perspective

20Hz resonant circuit for Rapid Cycling Synchrotron







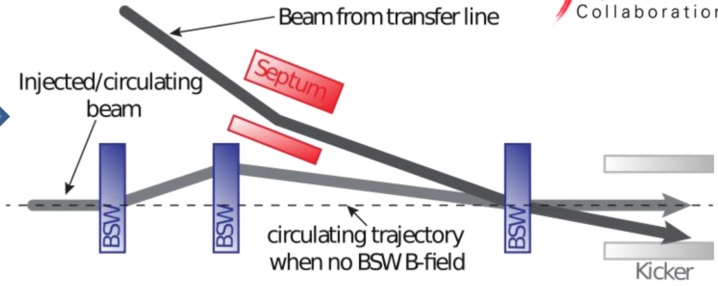


20Hz Rapid Cycling Quick ramp Synchrotron (RCQS)

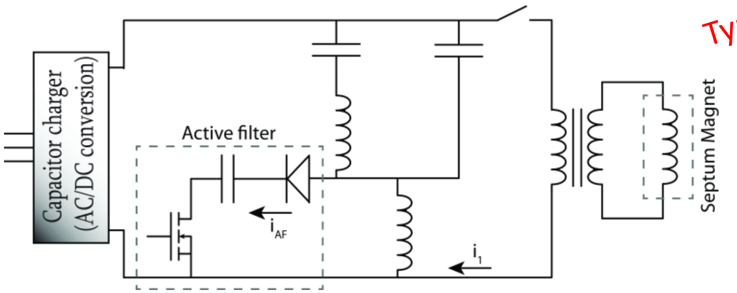
The capacitor discharge is indeed the technology we will investigate

Capacitor discharge power converters - CERN examples

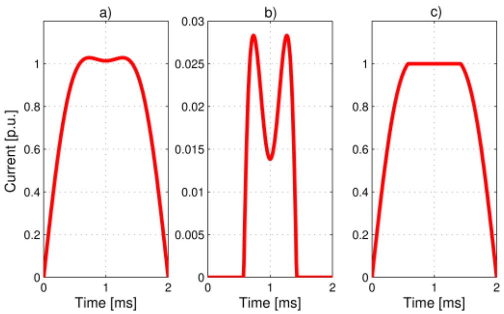
- Capacitor discharge-based converters applications at CERN
  - Used in *ms*-range pulsed applications → Bumper and slow septa magnets
  - Ranges from 10 A to 10 kA / 100 V to 4 kV (converter side) + adapting pulse transformer installed in proximity of magnet – typically need for a flat-top current
  - Vast majority of energy is regenerated back to capacitors after impulse
- What basic topologies?



Direct resonance – "single" HV switch



Typical @ CERN:
< 4 kV; 6 kA
2 Hz rep. rate

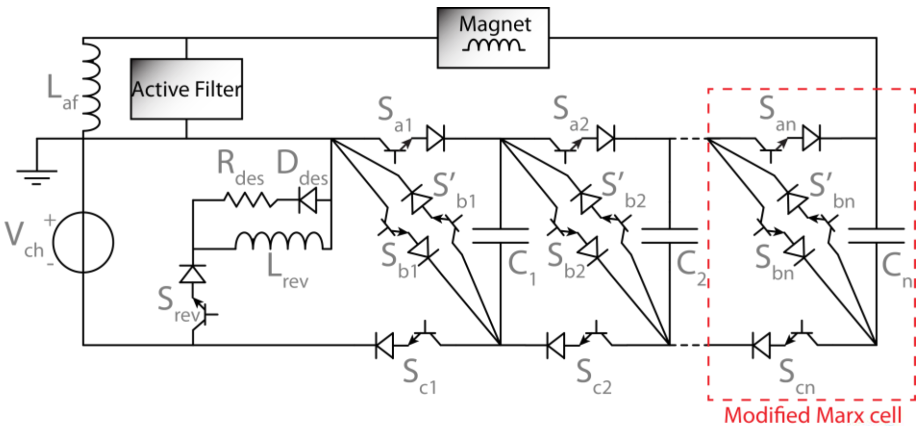


- Fundamental + 3rd harmonic injection to approach square shape
- Active filter (rated @ a fraction of nominal power) for flat-top fine tune
- Simple and reliable, but has HV charger and components
- All capacitor energy utilized

Direct resonance – spread LV switches (Marx topology)

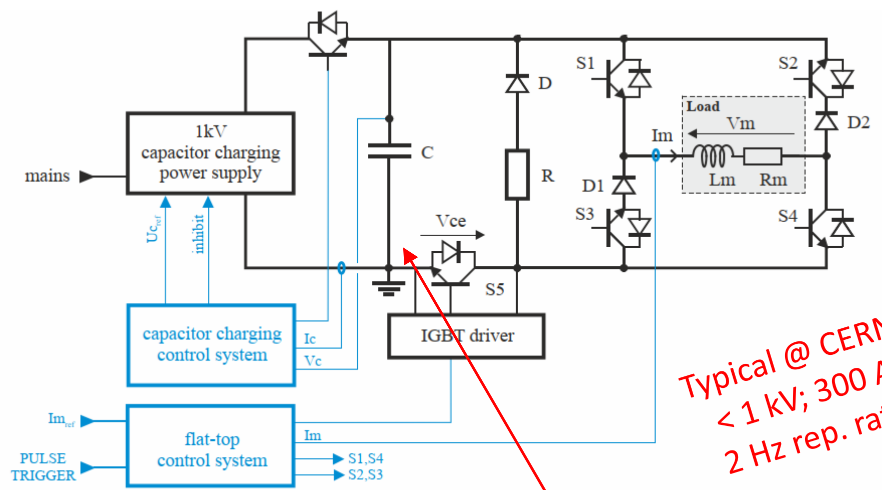
- Concept: Charge capacitors in parallel, discharge them in series
- Can be coupled with an active filter
- Low voltage charger and components (low voltage capacitors)
- …but more complex protection scheme…
- All capacitor energy utilized

Typical @ CERN:
< 8 kV; 2 kA
2 Hz rep. rate



Capacitor discharge power converters - CERN examples

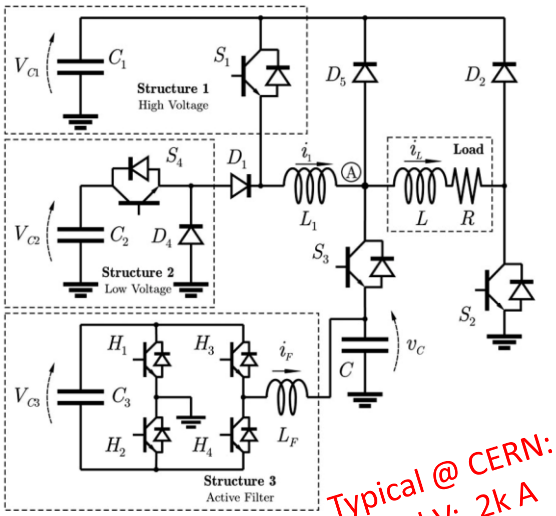
Semi-resonant – with linear active filter

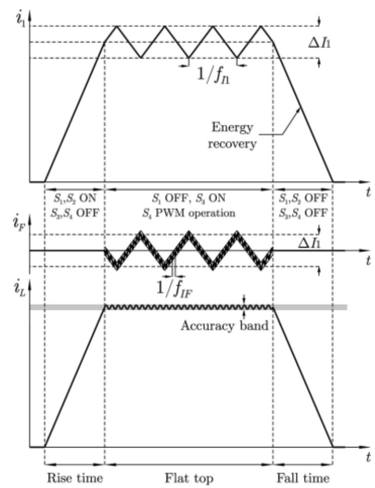


Typical @ CERN:
< 1 kV; 300 A
2 Hz rep. rate

Transistor operated in active region as "variable/controllable" resistor

Multiple stage (Switching)





Typical @ CERN:
< 3 kV; 2k A
2 Hz rep. rate

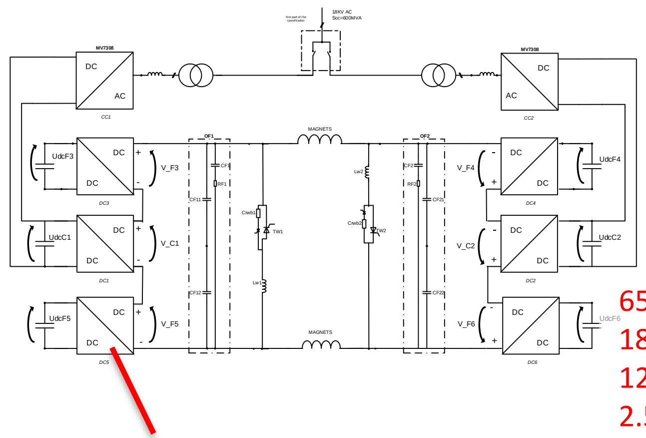
- Concept: Controlled discharge of the capacitor, via series IGBT controlled in its active region (active filter)
- Allows very high precision & dynamics (bandwidth)
- Active filter very lossy → adapted for small duty cycles or small powers (similar topology used for L4 source – 3 units only!)
- Tendency to replace this concept with high frequency switching technology (SiC & GaN)

- Concept - Stages at different voltages & current ratings
  - High power stage manages overall current shape
  - Medium power stage considered as coarse active filter
  - Small power stage as fine tune actine filter
- Flexible converter – works on wide magnet ind. values range
- Complex regulation – controllers for each stage start acting in a sequential way
- Only a fraction of energy stored in capacitor transferred to magnet

Capacitor Magnets slow energy exchange- CERN examples

POPS

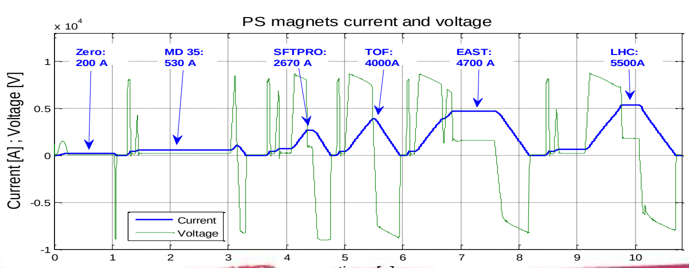
POPS: the main power system for the CERN PS accelerator



65 tons of 5kV capacitors
18 MJ installed
12MJ discharge unipolar
2.5 MCHF pure material

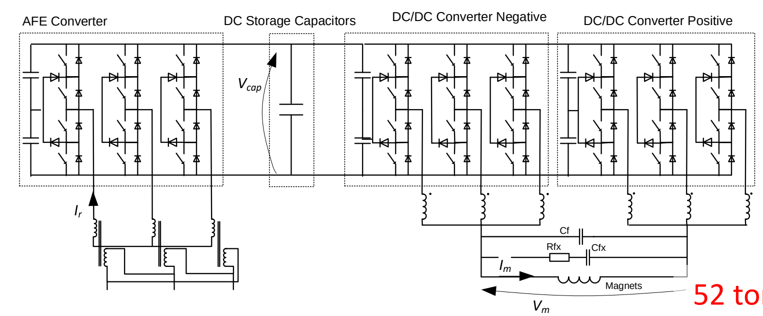
Press-pack IGBT. Very high cycling capability and lifetime

- Concept: NRG exchange between the Magnets and six 12m long capacitors containers
- Exchange perfectly controlled by the us of fully controllable DCDC converters
- Peak power on magnets is 60MW, with only 5MWpk taken from the network (constant profile)
- Rump-up/down is slow. Repetition rate is about 0.3Hz

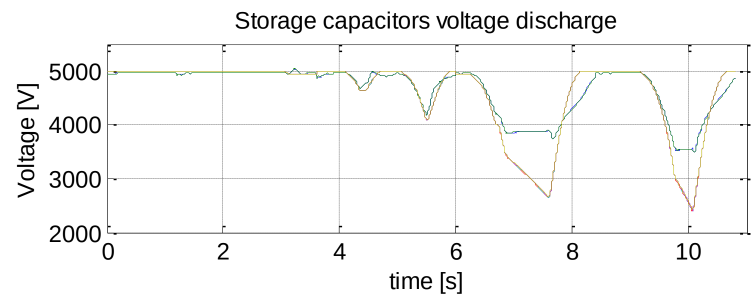


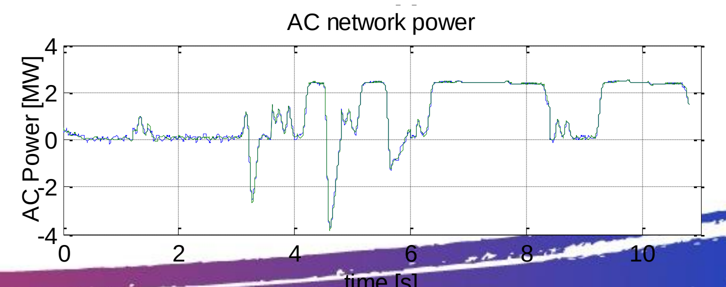
POPS-B

POPS-B: the main power system for the CERN PS-Booster accelerator



52 tons of 5kV capacitors
11 MJ installed
7MJ discharge unipolar
2 MCHF pure material

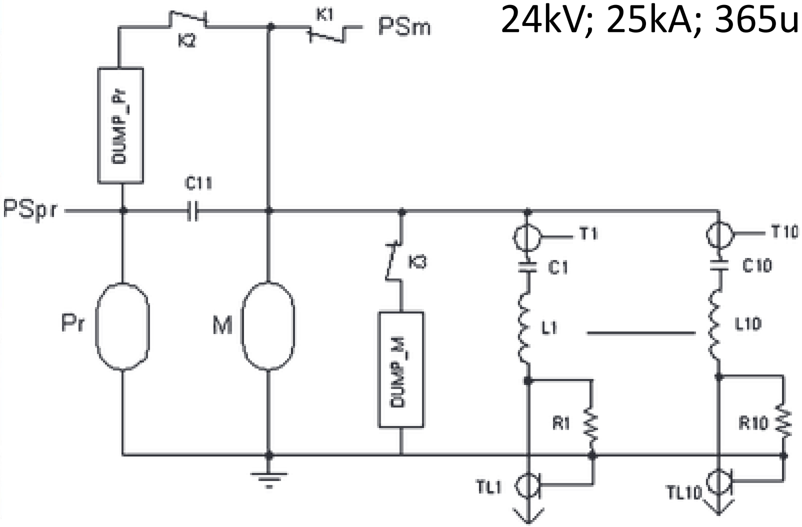




Capacitor discharge experiments: Laser Mega Joule

LMJ Energy banks

Facility for tests on nuclear weapons and confinement fusion experiments



24kV; 25kA; 365us x cell

24kV; 25kA; 365us x cell

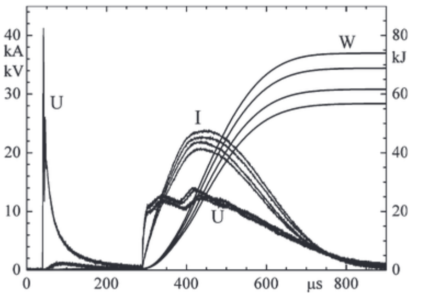


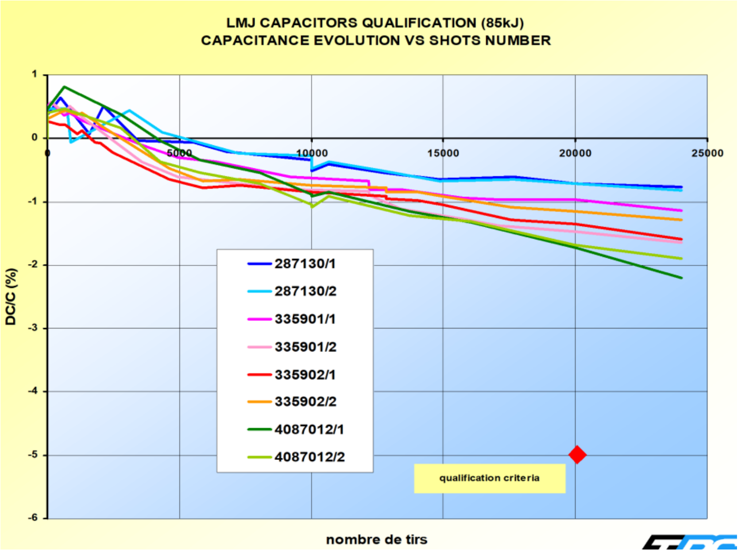
Fig. 6. Waveforms of voltage U, current I, and energy W on the flashlamps load for 21-, 22-, 23-, and 24-kV charging voltages.

480 Modules 850kJ = 408MJ Capacitor energy density = 900J/l

x 3520 caps

Huge NRG and Peak power but extremely low repetition rate and total number of pulses.
No voltage reversal.

Lifetime of capacitors is 34 minutes of Muon Collider operation.



Courtesy of M. Claude Vincent (AVX)

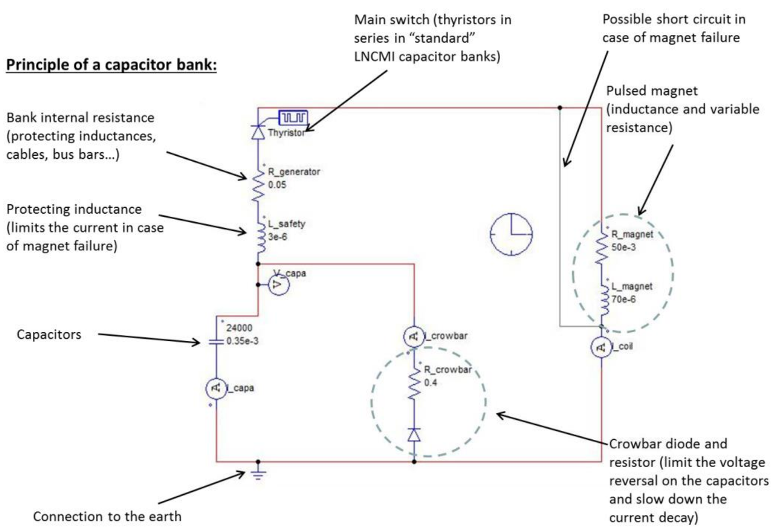
Capacitor discharge experiments: LNCMI

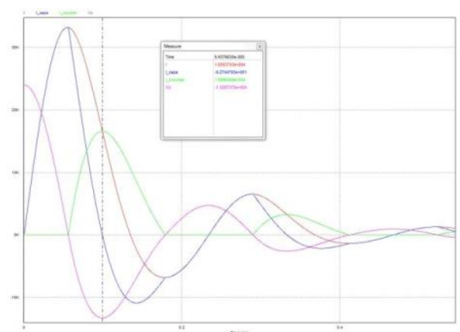
Laboratoire **N**ational des **C**hamps **M**agnétiques **I**ntenses

Capacitor discharge for high pulsed magnetic fields

24kV, 14.4kJ capacitors
Discharge current 40kA x capacitors in 40us with 60% voltage polarity reversal.

Very high peak power (2 GW for the complete bank) but low repetition frequency (0.016Hz).
Total number of pulses 100’000 i.e. 167 minutes of Muon collider

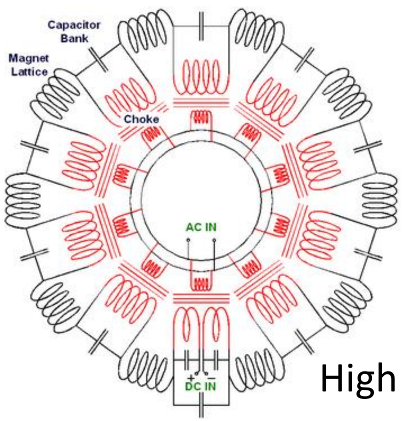




Courtesy of M. Jérôme Beard (LNCMI)

Muon Accelerator Power Supply System. A technology mix

High repetition rate (RCS typical use)



High precision Discap for continuous operation (Septum, Kickers typical use)

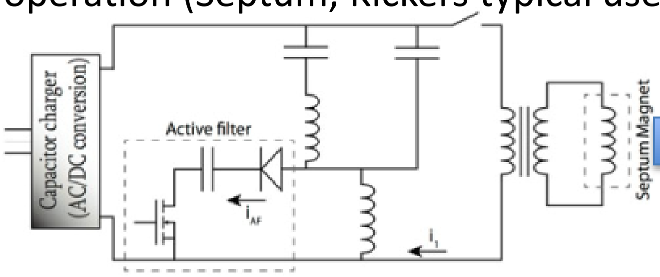
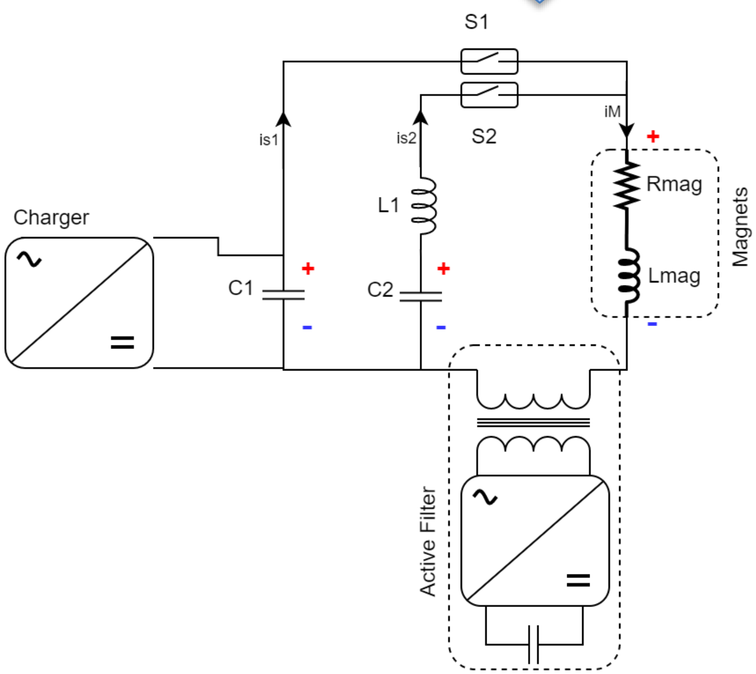
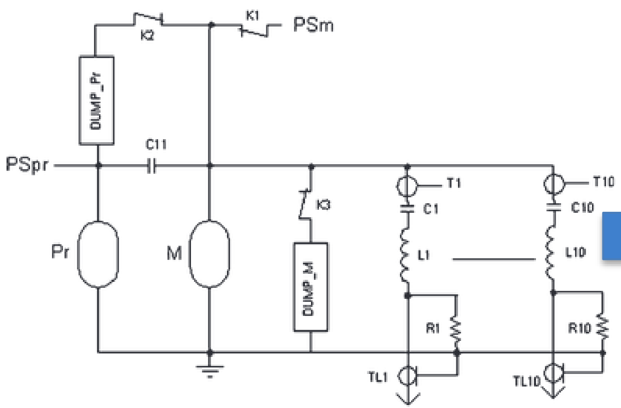


Fig. 4. 3[rd] harmonic injection + active filter concept [4].



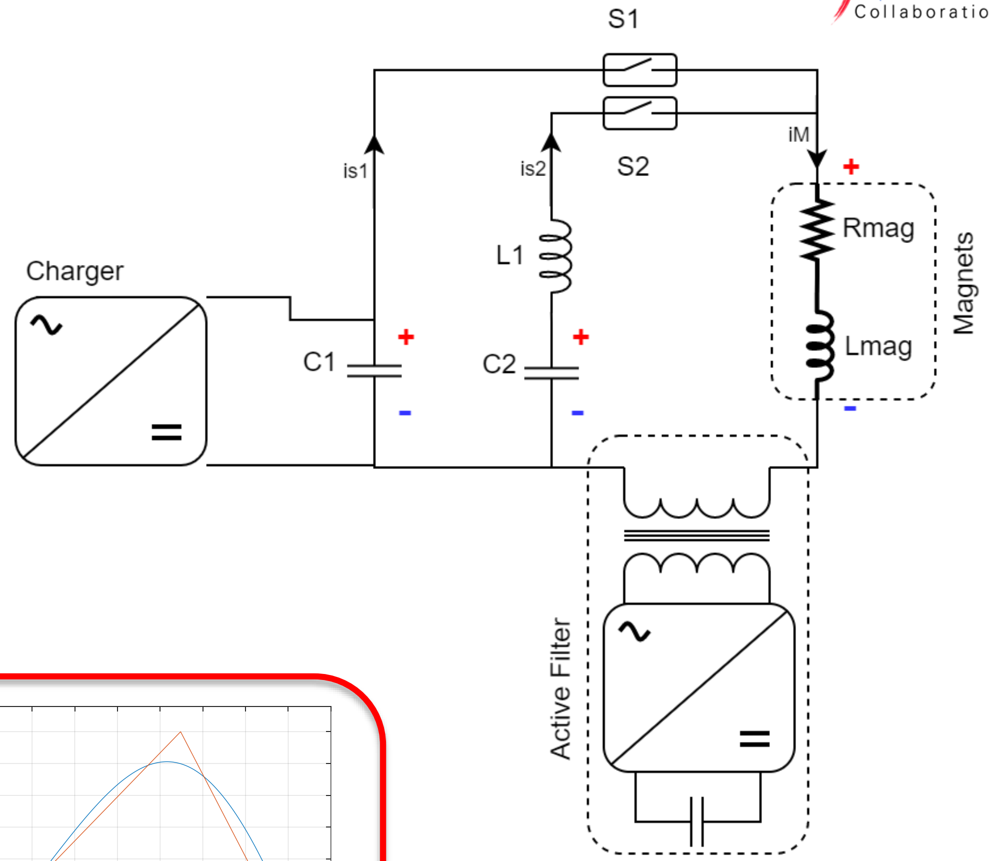
High energy and peak power (typical of laser or intense magnetic field experiments)

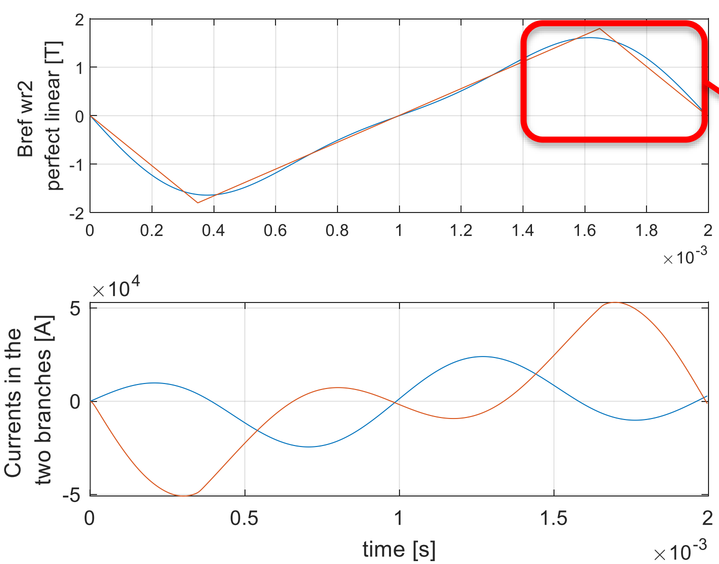


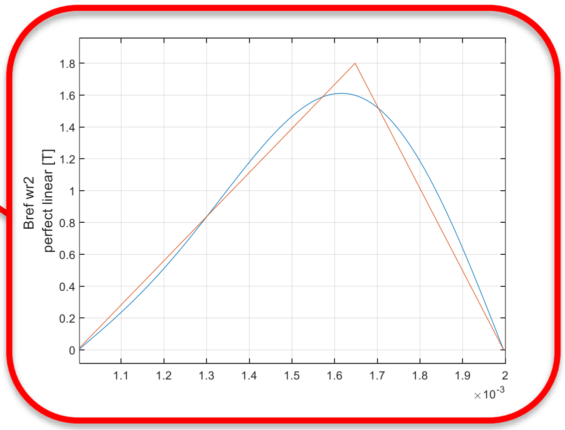
Muon Accelerator Power Supply System. Two harmonics circuit

Simple and generic circuit with double harmonics and active filter.
Two capacitor banks tuned to two different resonating frequencies

Two close-only switches that can be activated synchronously or asynchronously. Possibly based on semiconductor tech.







Two branches contribute to the total magnet current

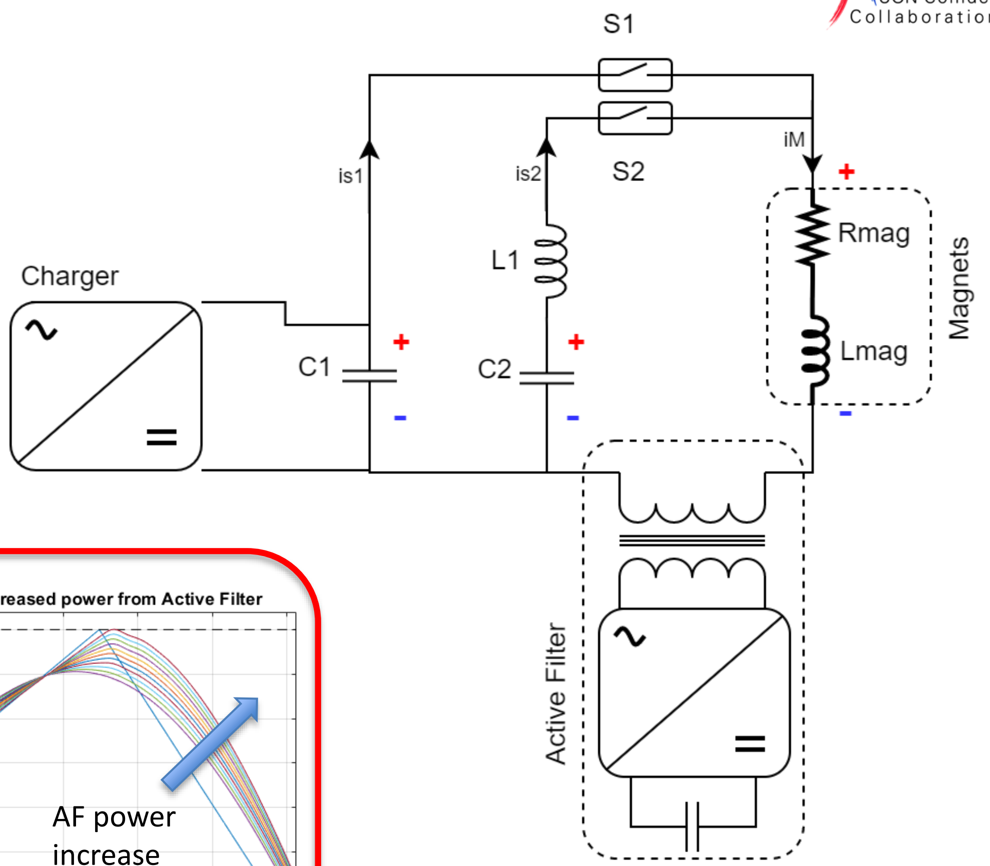
Muon Accelerator Power Supply System. Two harmonics circuit

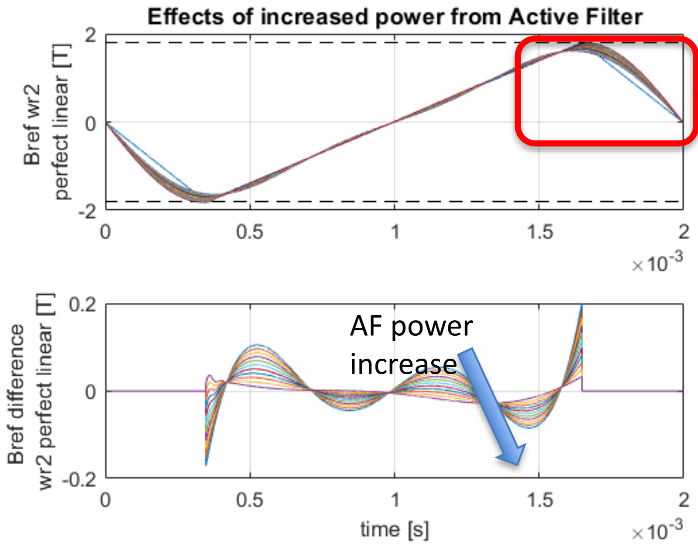
The Active Filter can be dimensioned:

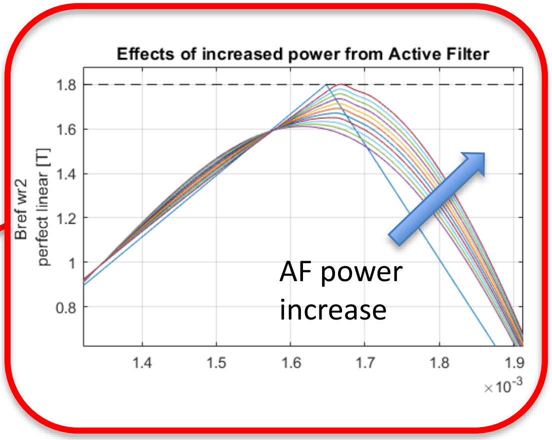
- to assure pulse to pulse repeatability
- to increase the linearity of the ramp
- to provide local correction in the shape of the ramp

Peak power provided by AF is much more expensive that the one provided by the capacitors.

AF contribution should therefore be limited as much as possible







Muon Accelerator Power Supply System. A possible layout

	RCS2
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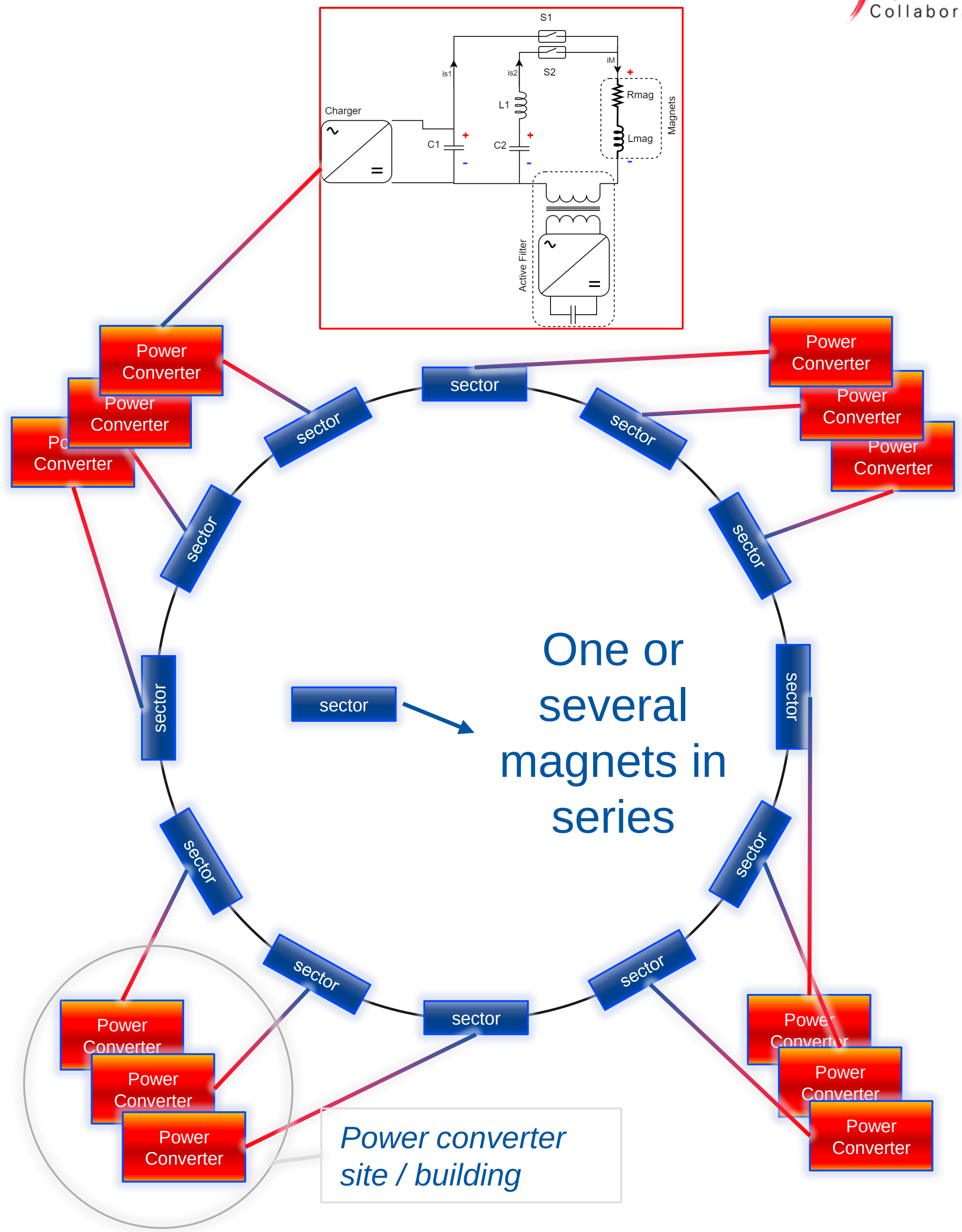
Repetition time Trep [ms]	100
dB/dt [T/s]	3200
NC magnet length [m]	2438
SC magnets length [m]	1416
NC dipole gap (hxw) [mmxmm]	30x90

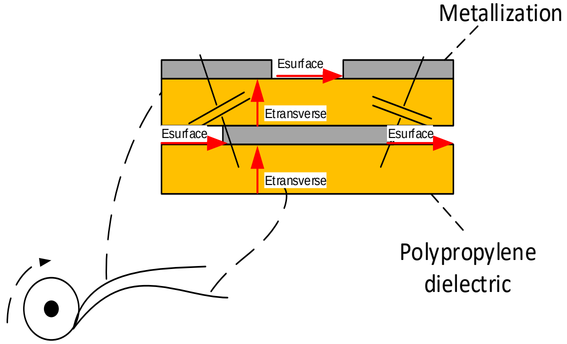
Order of magnitude values x sector	
Number of sectors	200
Peak current in magnets	45 kA
Peak voltage across magnets	15 kV
Peak current in branches	50 kA
Peak voltage on capacitors	30kV 100% polarity reversal
Peak power in magnet	300 MW
Stored NRG in capacitors	200 kJ

These values are for order of magnitude only. Calculation cases will be reported in next presentation tomorrow.



Muon Accelerator Power Supply System. Capacitors

$$C = \epsilon_0 \cdot \epsilon_r \frac{S}{d}$$

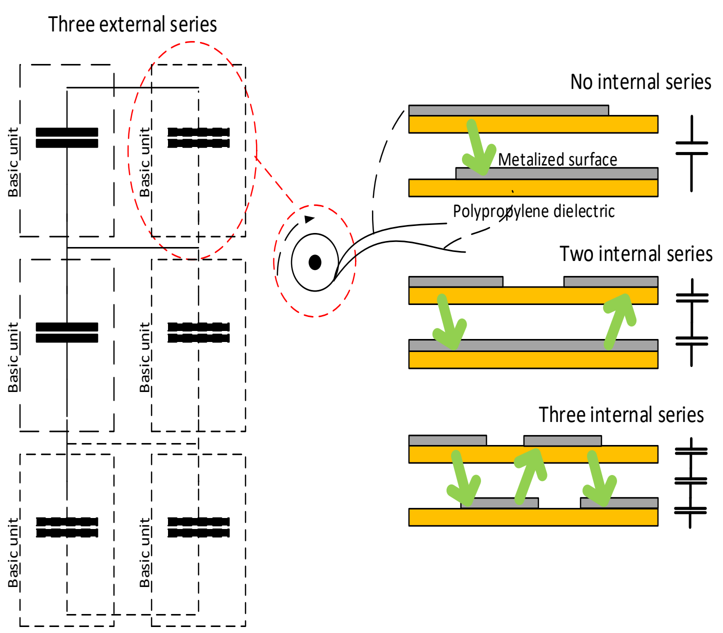


The lower d the higher the capacitance but at the price of Etransverse increase

Polypropylene metalized film capacitors.
Same type as those of the power converters previously discussed

$$E_{tr\_brdown} = 640 \; {}^{V}/_{\mu m} \qquad E_{tr\_brdown} = 810 \; {}^{V}/_{\mu m}$$

Series-parallel connection



$$E_{tr\_operation} = 50 \div 450 \, {}^{V}/_{\mu m}$$

$$NRG_{DENSITY} \propto E_{tr}^2 \propto V^2$$

Muon Accelerator Power Supply System. Capacitors

Ageing Factors: self healing

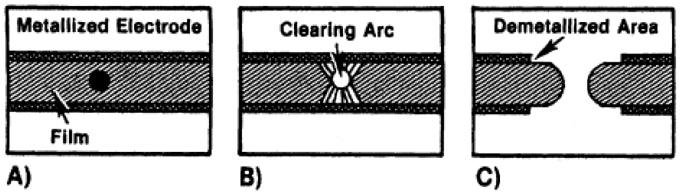


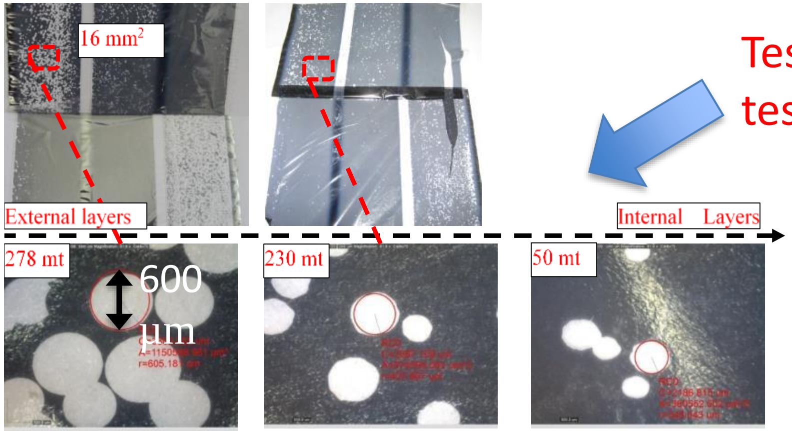
Fig. 2: Schematic diagram of the clearing sequence. A) Metallized film with a defect. B) Voltage applied between electrodes causes breakdown at the defect site and high fault current flows and C) heat from fault current vaporizes electrode and isolates the defect site.

Polypropylene metalized film capacitors are capable to self heal. Self heal comes with a loss of capacitance and it is therefore an ageing factor. The lower the Electric field, the lower the self-healing loss of C.

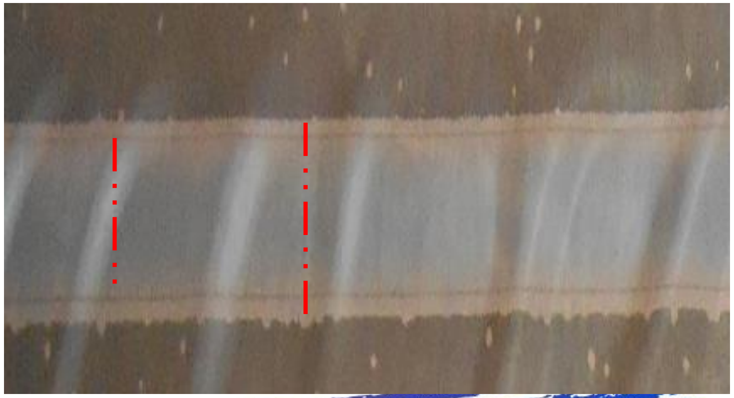
It is accepted to have short circuits in the design. Ex LMJ capacitors experience a large number of self healings but it’s OK because they only have to make 25’000 pulses in their lifetime.

Ageing Factors: Electrode corrosion

The AC content causes electrode erosion as corona inception or partial discharge in PP-oil interlayers. In polarity reversal the phenomena is much worse. This is one of the reason why AC capacitors have lower Etransverse than DC ones.



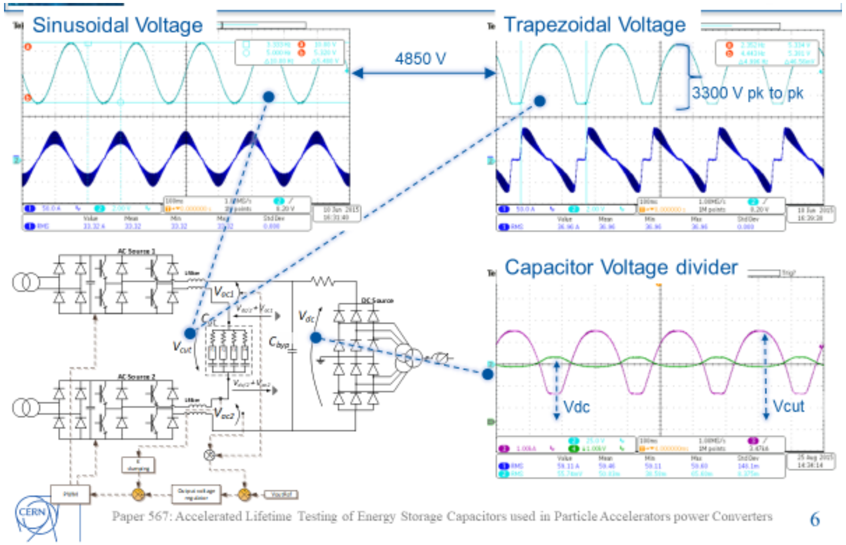
Tested at CERN in capacitor testing laboratory



Muon Accelerator Power Supply System. Capacitors

Metalized PP film capacitors: the CERN experience

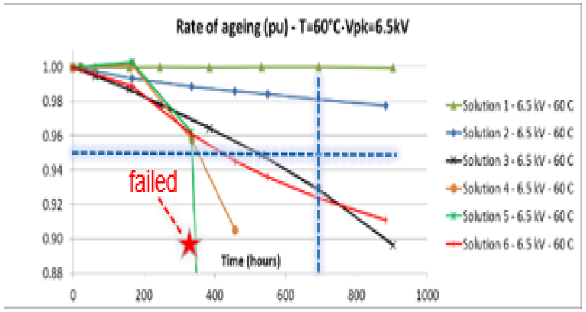
Built a testing lab for POPS and POPSB capacitors qualification

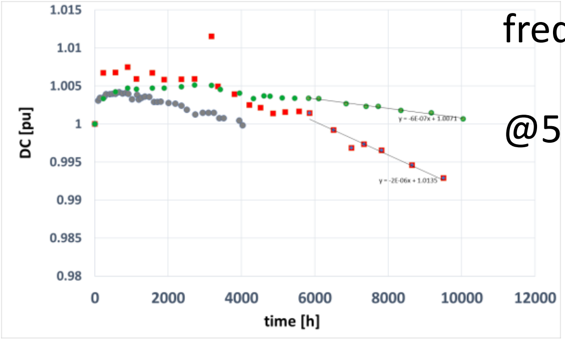


Reduced scale samples

Full scale unit

Qualification and quality tests





Up to 10’000h pulses in accelerated testing with higher temperature and peak voltage and frequency

@5Hz ageing testing, it makes 180Mpulses

Muon Accelerator Power Supply System. Capacitors

What Capacitors and NRG density for the Muon accelerator?

Metalized film PP capacitors are the ideal candidate because they are robust, capable of very high and quick current pulses and protected by the self-healing.

First discussions with supplier:

Comparing the application to POPS and considering that POPS has a gradient of 250V/um, we can calculate the NRG density relative to POPS by calculating the ratio of the squares of the transverse electrical fields:

Mostly because of 100% voltage polarity reversal and high repetition frequency

$$NRG_{DensityMUco} = NRG_{DensityMUco} \cdot \left[\frac{E_{MuCo}}{E_{POPS}}\right]^2 = 274\,{}^{J}/_{l} \cdot \left[\frac{65\,{}^{V}/_{\mu m}}{250\,{}^{V}/_{\mu m}}\right]^2 = 274\,{}^{J}/_{l} \cdot \frac{1}{15}$$

POPS capacitor container.
12mx2.5mx2.5m; 26tons; 3.3MJ; 0.5MCHF;

Muon Accelerator capacitor container.
12mx2.5mx2.5m; 26tons; 0.22MJ; 0.5MCHF

<u>Test could help reducing this number</u>

Muon Accelerator Power Supply System. Conclusions

- In particle accelerator jargon, RCS indicates a system that has a high repetition rate, but not necessarily a quick ramp. Muon accelerator will need a RCSQS.
- Double harmonics capacitor discharge plus active filter, is quite general topology that can be considered as basic tool for the analysis of the Muon Accelerator powering system. Applications in much lower power for fast pulsed magnets (Kickers, septums and bumpers), are well consolidated examples.
- Power electronics (the Active Filter) is dimensioned on peak power, therefore its contribution should be limited in order to limit investment costs
- Capacitors are among the most relevant components. Initial projection on NRG density seem quite low. Tests could maybe help in getting higher values